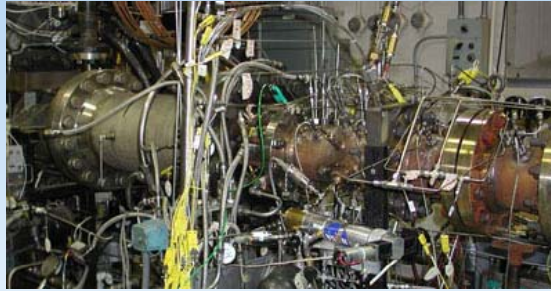


Combustion Dynamics and Control for Ultra Low Emissions in Aircraft Gas-Turbine Engines

Future aircraft engines must provide ultra-low emissions and high efficiency at low cost while maintaining the reliability and operability of present day engines. The demands for increased performance and decreased emissions have resulted in advanced combustor designs that are critically dependent on efficient fuel/air mixing and lean operation. However, all combustors, but most notably lean-burning low-emissions combustors, are susceptible to combustion instabilities. These instabilities are typically caused by the interaction of the fluctuating heat release of the combustion process with naturally occurring acoustic resonances. These interactions can produce large pressure oscillations within the combustor and can reduce component life and potentially lead to premature mechanical failures.

Active Combustion Control which consists of feedback-based control of the fuel-air mixing process can provide an approach to achieving acceptable combustor dynamic behavior while minimizing emissions, and thus can provide flexibility during the combustor design process. The NASA Glenn Active Combustion Control Technology activity aims to demonstrate active control in a realistic environment relevant to aircraft engines by providing experiments tied to aircraft gas turbine combustors. The intent is to allow the technology maturity of active combustion control to advance to eventual demonstration in an engine environment. Work at NASA Glenn has shown that active combustion control, utilizing advanced algorithms working through high frequency fuel actuation, can effectively suppress instabilities in a combustor which emulates the instabilities found in an aircraft gas turbine engine. Current efforts are aimed at extending these active control technologies to advanced ultra-low-emissions combustors such as those employing multi-point lean direct injection.

Combustion Dynamics and Control for Ultra Low Emissions in Aircraft Gas-Turbine Engines



John DeLaat

Controls and Dynamics Branch

NASA Glenn Research Center at Lewis Field, Cleveland, OH

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*Graduate Seminar Series, The Ohio State University
May 9, 2011*

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Outline

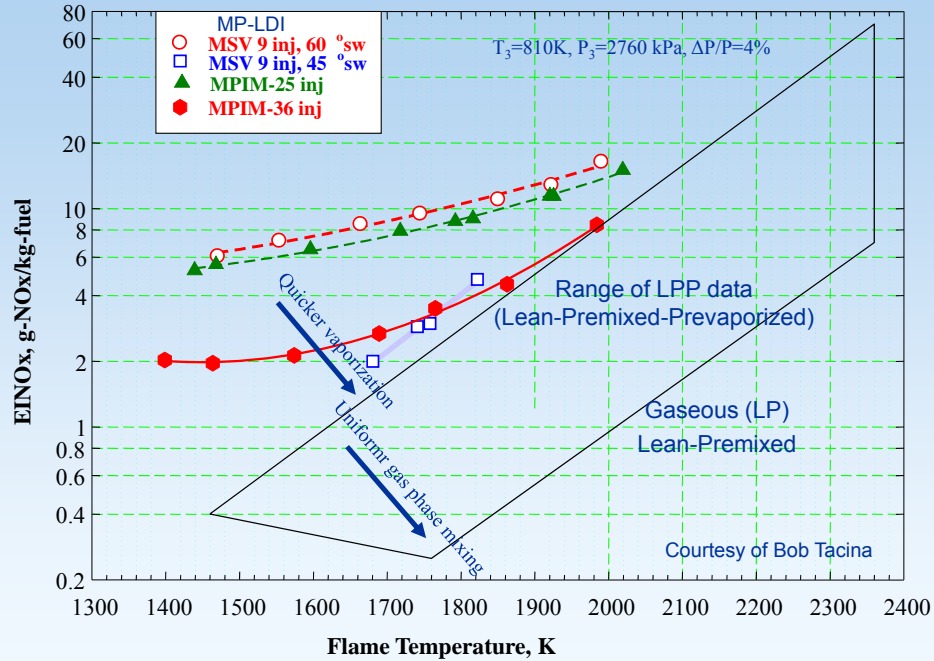
- NASA's Active Combustion Control interests
- Motivation: Ultra-low emissions, lean-burning, Multi-point Lean Direct Injection combustors
 - More susceptible to instability
- Possible approaches for dealing with combustor thermo-acoustic instabilities
- Active Combustion Control as an enabling technology
- Approach and outcomes of instability control experiments
- Future plans

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Effect of Fuel Injection Schemes on NOx Emission

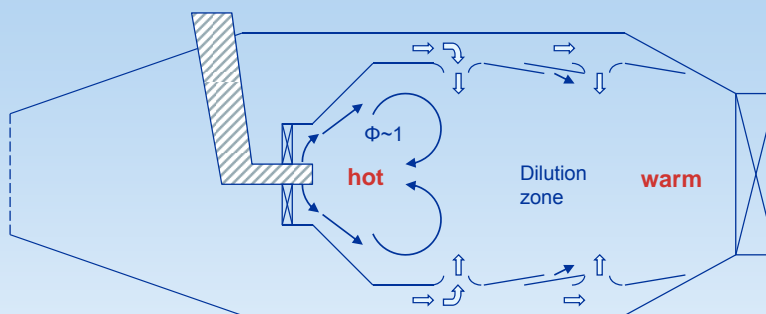


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Conventional Combustion: Single-Point Rich Front End Injection

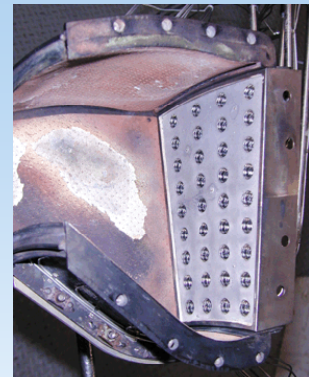
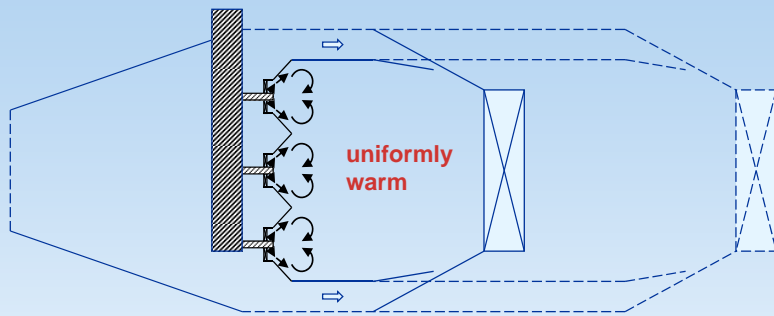


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Lean-Burning, Ultra-Low-Emissions Combustion: Multi-Point Lean Direct Injection



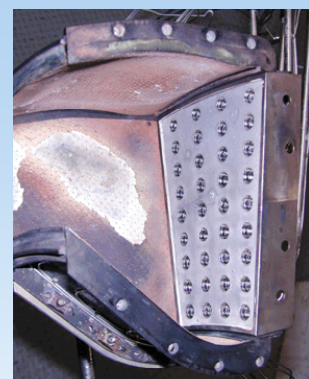
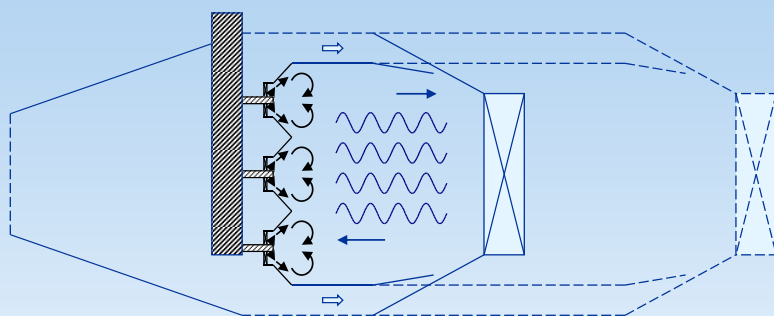
1. Energetic quick-mixing before auto ignition at high power condition
2. Lean and uniform front end makes less CO and NOx initially
3. Less CO initially, shorter combustor needed
4. Shorter combustor, shorter residence time, less additional NOx

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Lean-Burning, Ultra-Low-Emissions Combustors Are More Susceptible to Thermoacoustic Instabilities



1. Higher performance fuel injectors => more turbulence
2. No dilution air => reduced flame holding
3. Reduced film cooling => reduced damping
4. More uniform temperature distribution => acoustically homogeneous
5. Shorter combustor => higher frequency instabilities

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How do we deal with combustor instabilities?

1. Smart design
2. Modulate air to get out-of-phase cancellation
3. Fuel-modulation to get out-of-phase cancellation

Method 1 is preferred, but we're not sure it's enough

Method 2 requires lots of actuation power input and bulk

Method 2 also may induce diffuser flow separation due to flow perturbation.

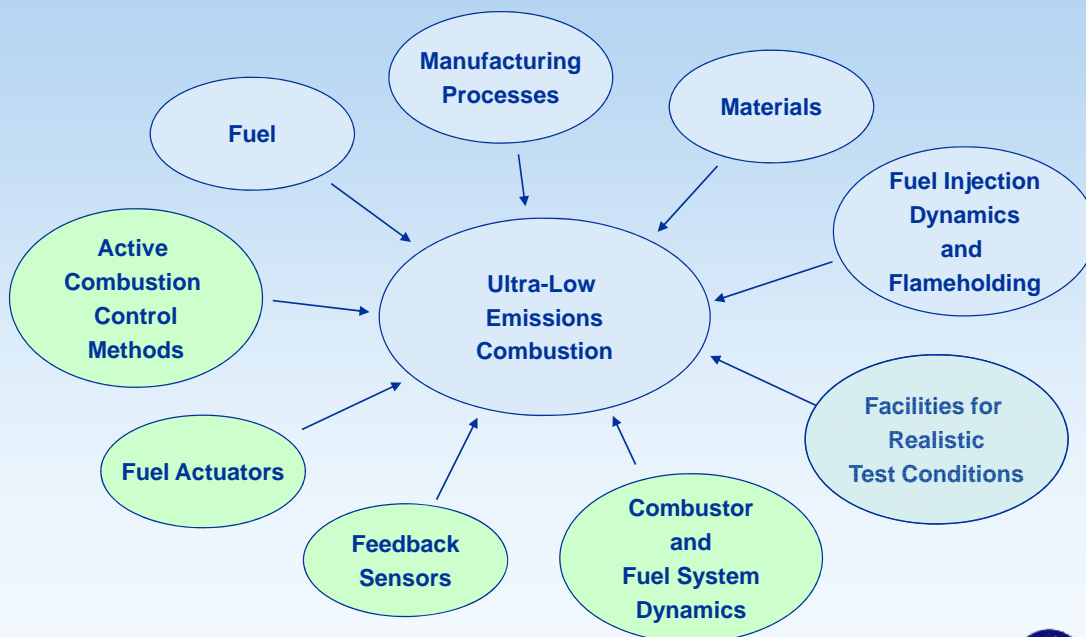
Method 3 requires the least actuation power and bulk and produces the most energy change

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Synergistic Technologies to Enable Ultra-Low Emissions Combustion

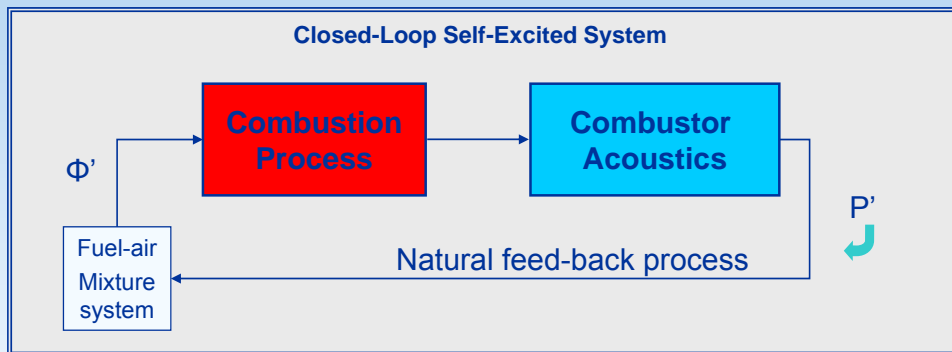


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Combustion Instability



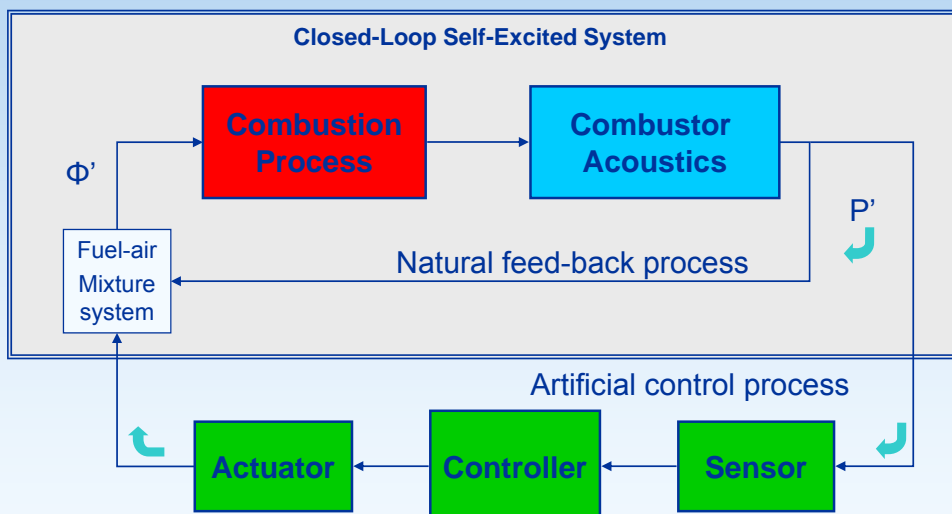
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Combustion Instability Control Strategy

Objective: Suppress combustion thermo-acoustic instabilities when they occur



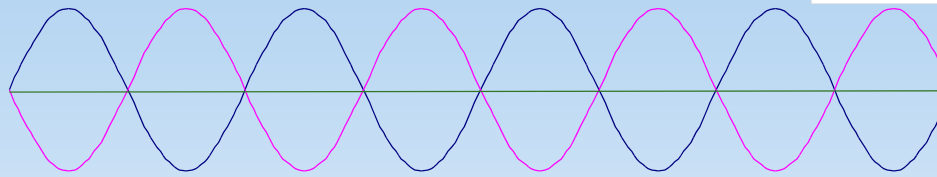
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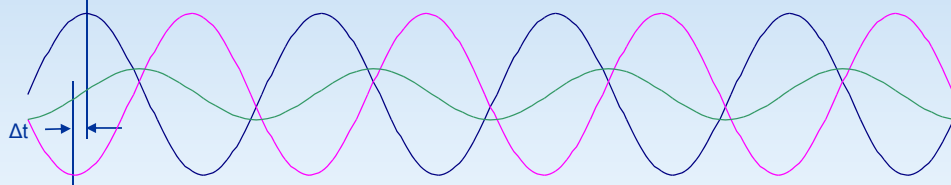


Why is instability control so difficult?

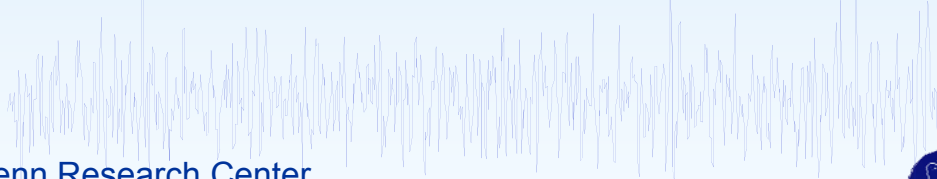
Phase inversion



Time delay & phase shift



Low signal-to-noise ratio – What frequency? What phase?



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Our Technical Challenges

- Control methods required to:
 - identify instability
 - suppress instability in presence of large time delay, substantial noise
- Combustor dynamics largely unmodeled
- Liquid fuel – introduces additional unmodeled dynamics including time delay (atomization, vaporization, ...)
- Actuation system – enough bandwidth and authority, not just valve (also feedline, injection, ...)
- Experimental testbed for actuation, feedline dynamics required
- Simplified models needed for control design evaluation

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Active Combustion Instability Control Via Fuel Modulation

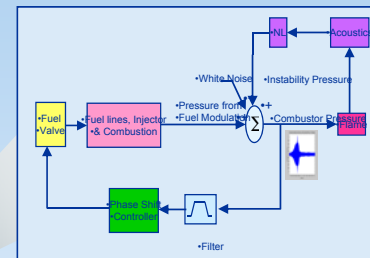
High-temperature sensors and electronics



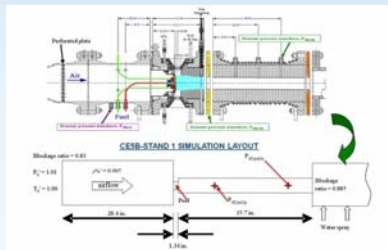
High-frequency fuel delivery system and models



Advanced control methods



Physics-based instability models



Realistic combustors, rigs for research

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Team Members - from Multiple Disciplines

- Controls and Dynamics Branch
 - Dan Paxson: Dynamic Models
 - George Kopasakis: Control Methods
 - Joe Saus: Actuators
- Combustion Branch
 - Clarence Chang: Combustion Science
- Sensors and Electronics Branch
 - Robert Okojie: Harsh Environments Pressure Sensors
- Engineering Directorate
 - Dan Vrnak: Control Software
- Supersonics Project
 - Dan Bulzan – Supersonics (and Subsonics) Combustion API
- Other NASA Participants
 - Materials, Combustion and Flow Diagnostics, Experimental Staff,...
- NRA Participants
 - Georgia Tech, Penn State, Virginia Tech
 - Other NRA's associated with Combustion Science

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Control Strategies to Deal with Combustion Instability

- Objective
 - Perturb the fuel with the right amplitude and at the right phase to cancel the instability
- Challenges
 - Control action delay, noise, unknown disturbances
- Approach
 - Use reduced-order models for development
 - Use simplified physics-based model for validation before test
- Control methods
 - Empirical: Adaptive phase shifting based on achieved cancellation
 - Model-based: Set the proper phase for cancellation based on a model of the predicted instability and disturbances

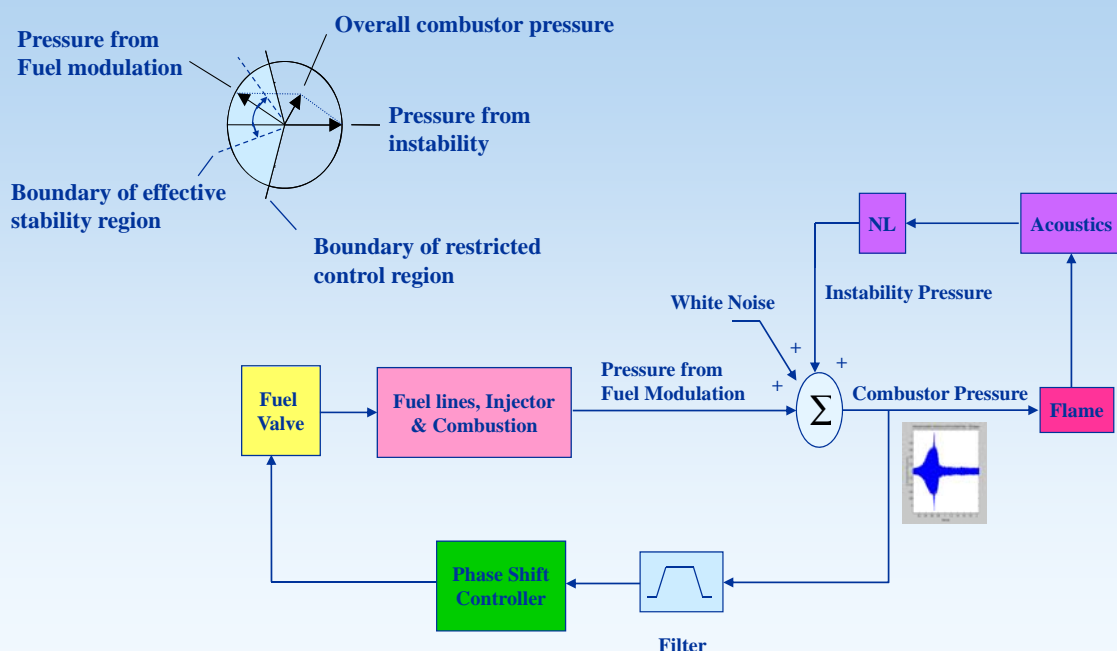
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Adaptive phase shifting control:

“Adaptive Sliding Phasor Averaged Control” – G. Kopasakis



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Motivation for Combustion Instability Simulation

- **Successful active control design requires accurate modeling and simulation.**
 - The essential physical phenomena should be correctly captured
 - (e.g. self-excitation).
 - Characterization and control design necessitate rapid simulation
 - (i.e. relative simplicity).
 - Simulation must lend itself to implementing a variety of sensing and actuation strategies.
- **The developed simulation method must achieve these goals for combustor configurations:**
 - in which the potential instabilities propagate axially
 - that contain abrupt changes in cross sectional area

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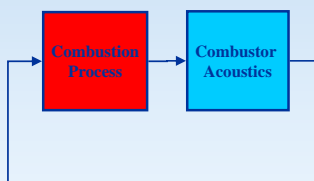


Combustion Dynamics Modeling



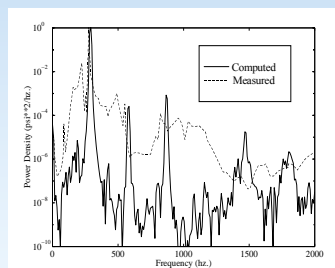
Reduced-order oscillator models

Run fast to allow parametric studies in support of control system development



Simplified Quasi-1D dynamic models

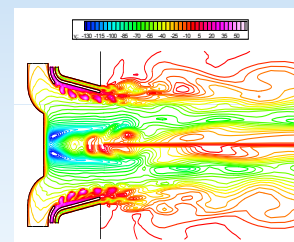
Allow physics-based control method validation



**Results from NASA
Sected-1D Model of
LPP Combustor Rig**

Detailed, physics-based dynamic models

Fundamental understanding of combustor dynamics to aid passive, active instability suppression



**Penn State Injector
Response Model Plot**

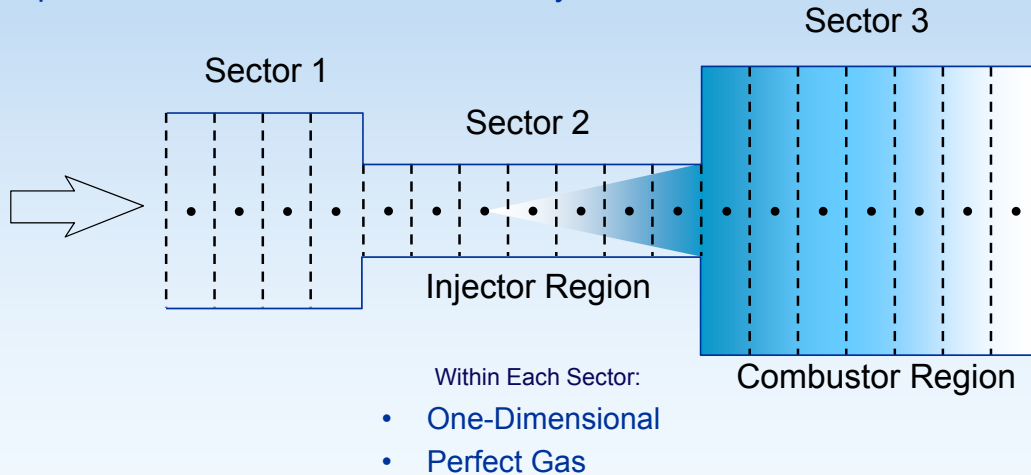
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Combustion Instability Simulation Features

- Time-accurate
- Physics-based, Sectored 1-D, Reacting
- Computationally efficient area transitions
- Upstream and Downstream boundary conditions modeled to match rig

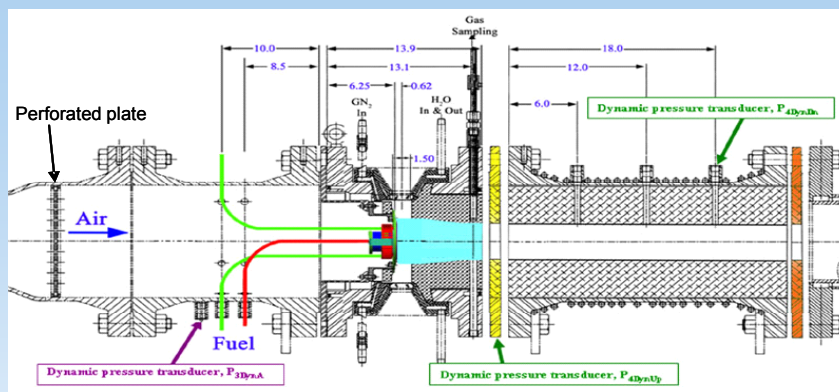


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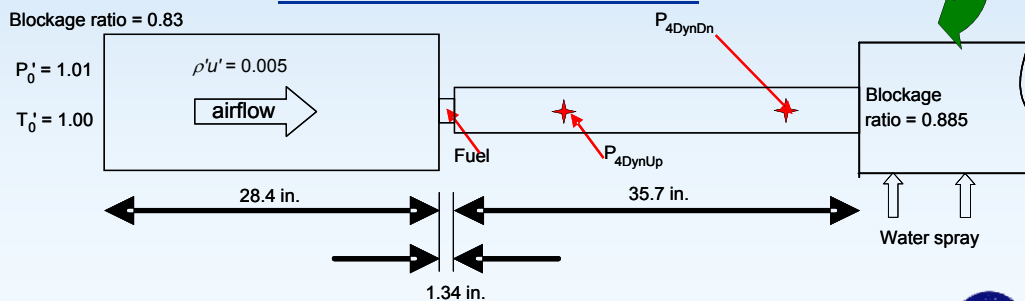
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Low Emissions Combustor Instability Model Development



CE5B-STAND 1 SIMULATION LAYOUT

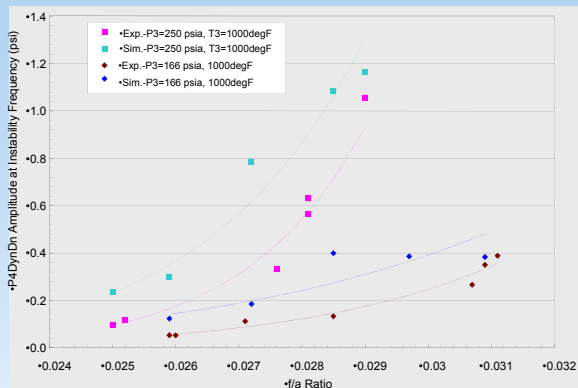


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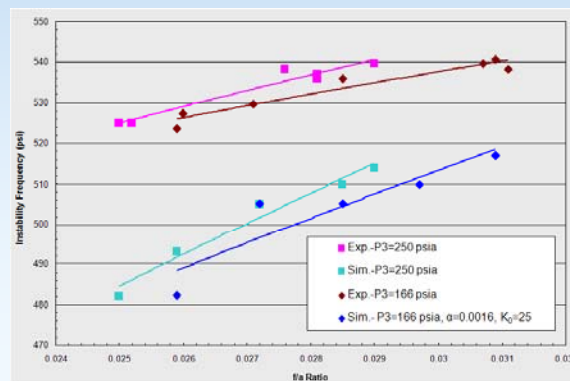


Combustion Instability Simulation Results Match Experimental Results for Multiple Operating Conditions



Amplitude trend replicated

Frequency trend replicated

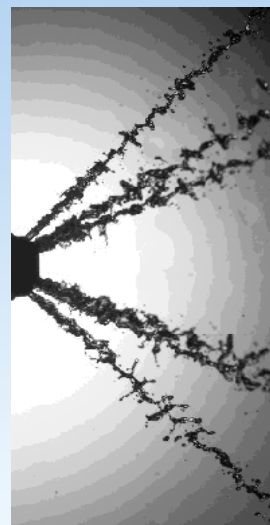
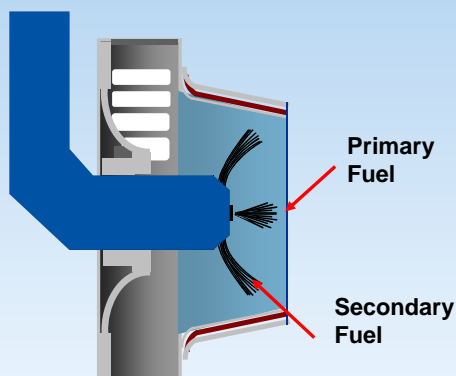


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Fuel Delivery System Dynamic Response



Stroboscopic Image of Dynamic Fuel Injection (courtesy UTRC)

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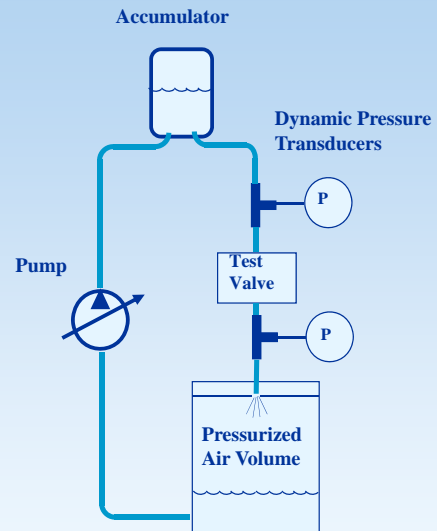
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High-Bandwidth Fuel Actuator Characterization Testing



Valve, Feed-system Characterization Rig at NASA GRC



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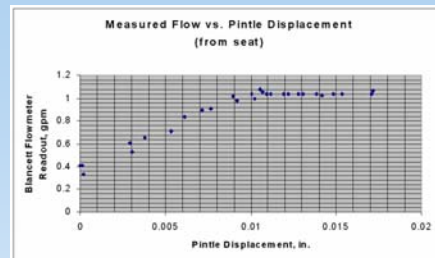
High-Bandwidth Fuel Actuator



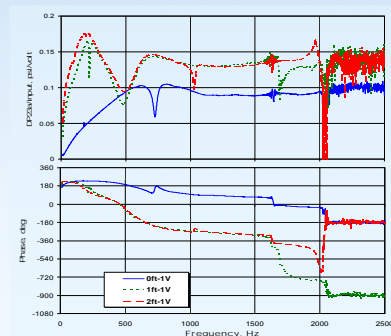
GaTech high-response fuel valve in characterization rig in CE7A



Steady-State Operational Data



Frequency Response Dynamic Characterization Data



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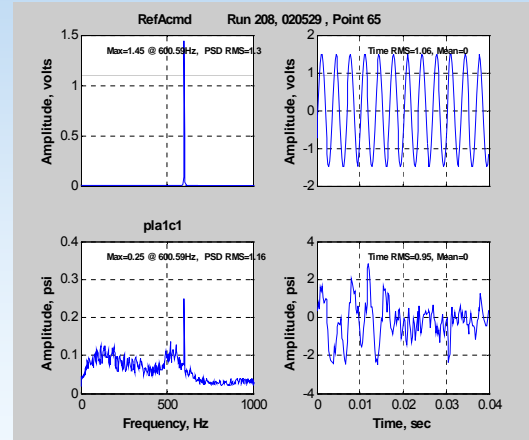
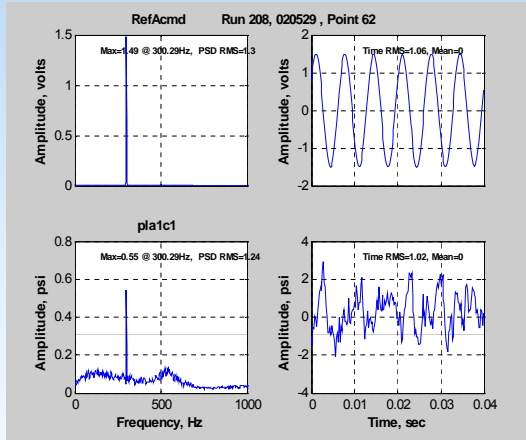


High-Bandwidth Fuel Actuator

Combustor Pressure Response to Fuel Modulation

300Hz

600Hz



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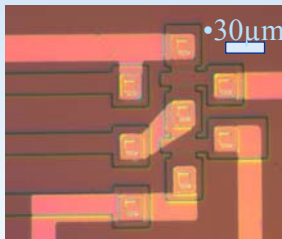
High Temperature Dynamic Pressure Sensors and Electronics



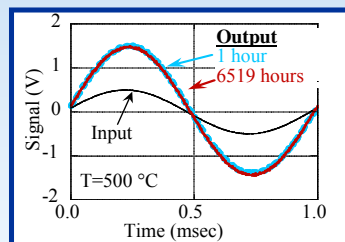
Newly developed 800°C sealing glass demonstrated on a dummy sensor and AIN package header.



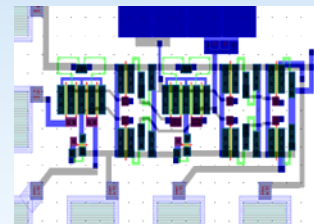
Modified MEMS-DCA package to support 800°C pressure sensor operation.



Differential amplifier circuit using two SiC transistors.



Diff amp test waveforms showing <5% change despite 6500 hrs at 500 °C.



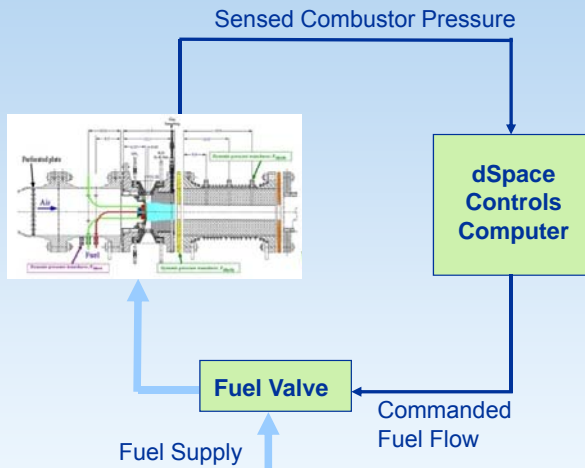
Design of SiC amplifier for dynamic pressure sensor.

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Combustion Instability Control Test Implementation



- Control methods implemented in real-time computer
- Rig operated at nominal engine temperature and pressure

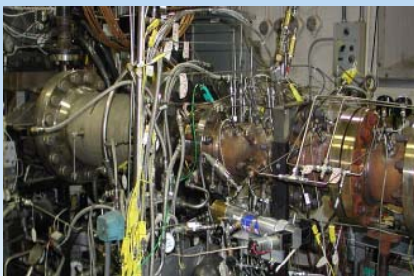
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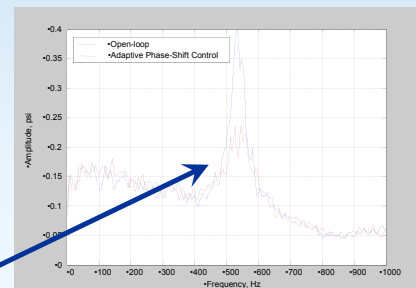
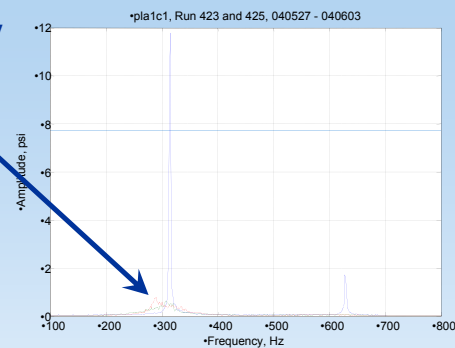
Active Combustion Instability Control Demonstrated Experimentally for Conventional Combustor

Large amplitude, low-frequency instability suppressed by 90%



Liquid-fueled combustor rig emulates engine observed instability behavior at engine pressures, temperatures, flows

High-frequency, low-amplitude instability is identified, while still small, and suppressed almost to the noise floor.



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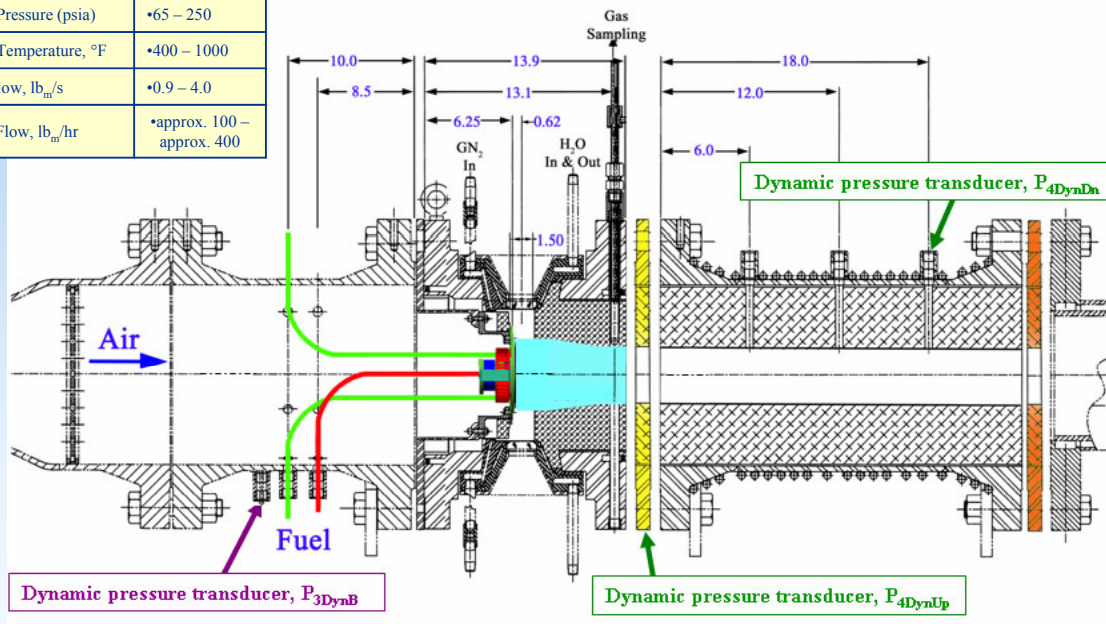
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Low-Emissions Combustor Prototype with Observed Instability

•Range of Combustor Operating Conditions

| | |
|---------------------------------|----------------------------|
| •Inlet Pressure (psia) | •65 – 250 |
| •Inlet Temperature, °F | •400 – 1000 |
| •Air Flow, lb _m /s | •0.9 – 4.0 |
| •Fuel Flow, lb _m /hr | •approx. 100 – approx. 400 |

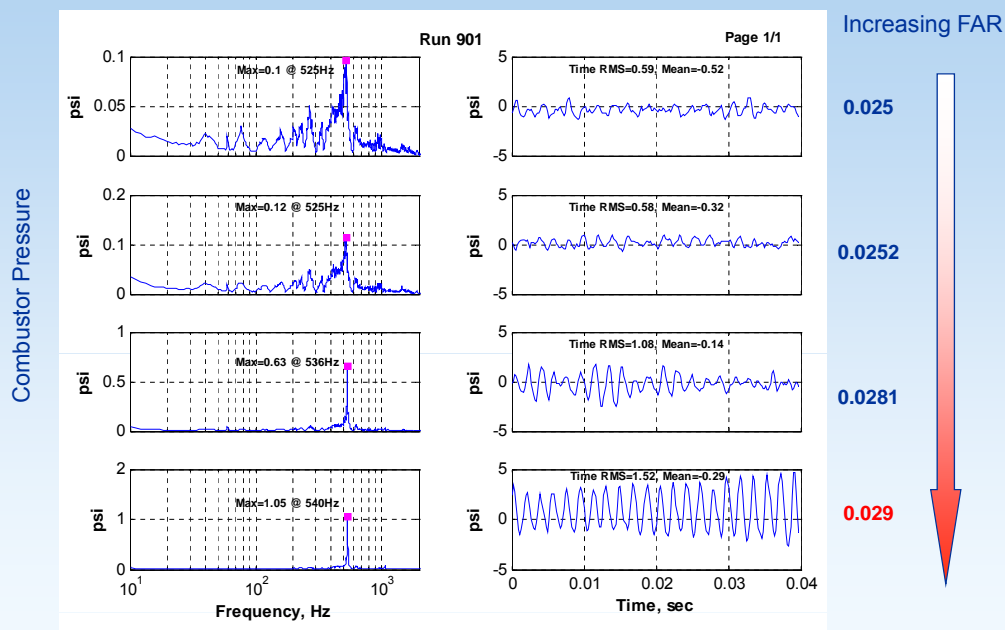


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Low-Emissions Combustor Prototype Instability Amplitude Observed to Increase with Increasing Fuel/Air Ratio

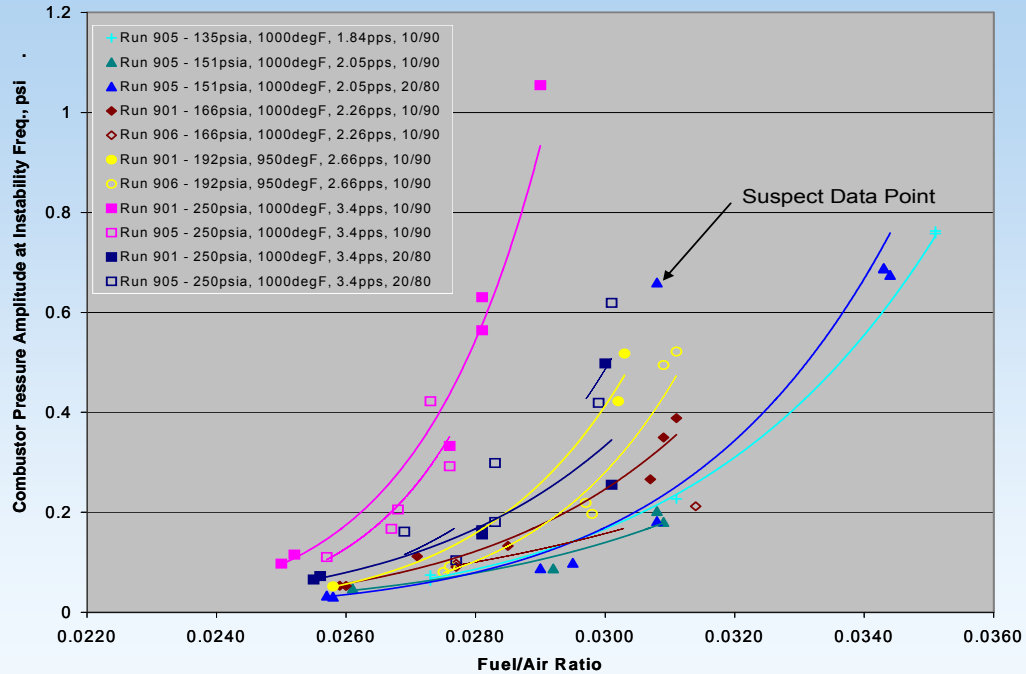


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Trend in Instability Amplitude vs. FAR for Multiple Test Runs

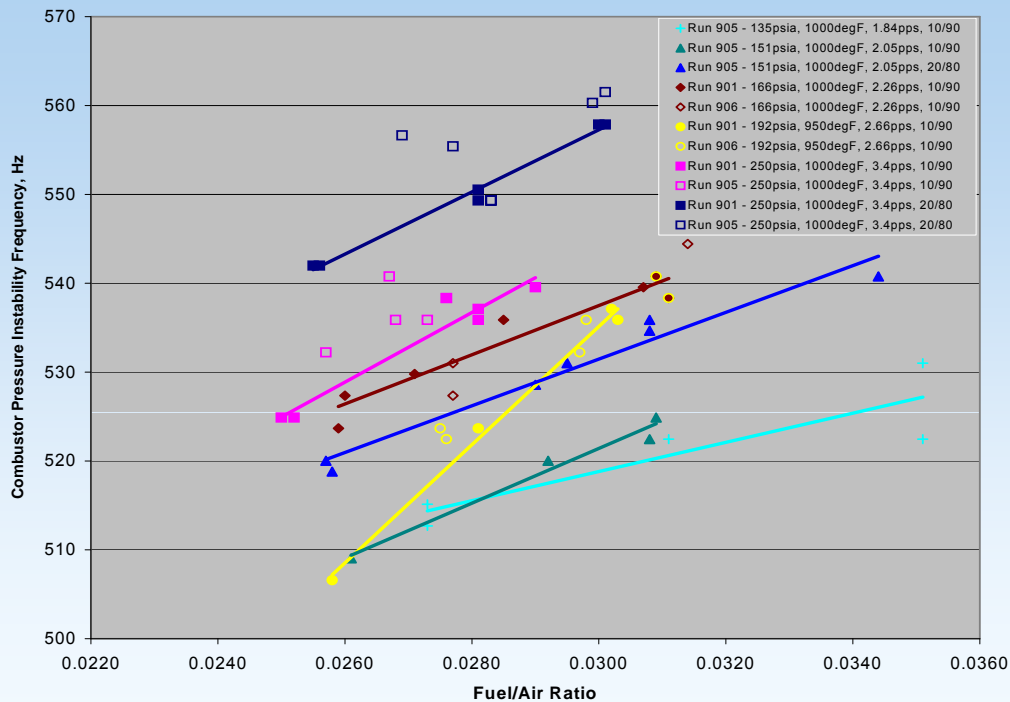


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Trend in Instability Frequency vs. FAR for Multiple Test Runs

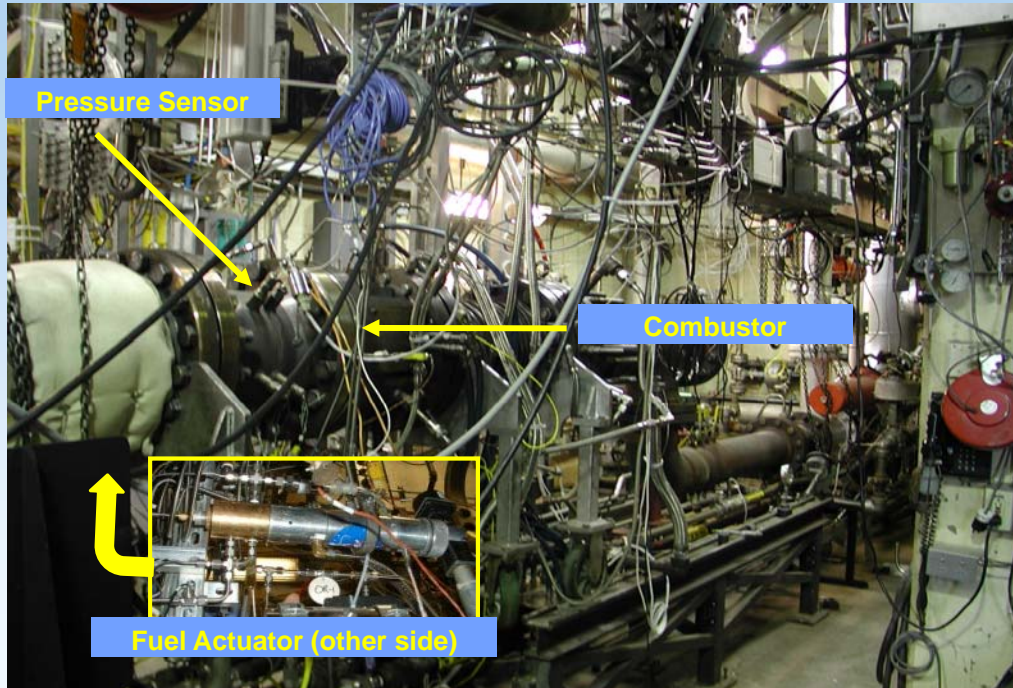


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Low-Emissions Combustor Prototype with Observed Instability as installed in CE5B-Stand 1



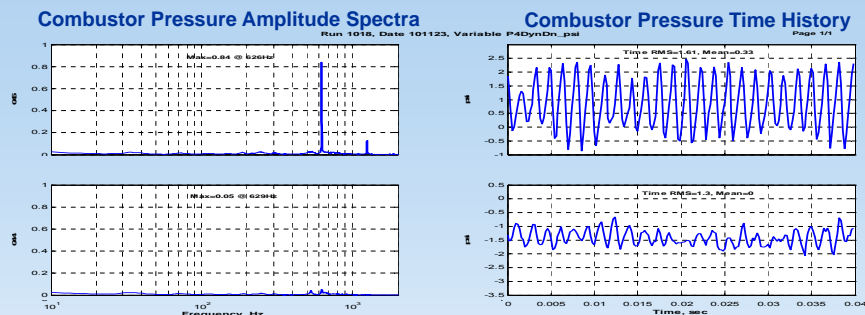
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Low-Emissions Combustor - Instability Control Results

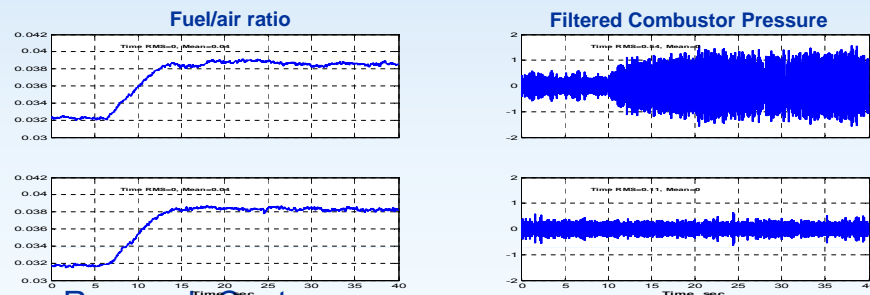
Adaptive Sliding Phasor Averaged Control (ASPAC) able to suppress combustion instability



Uncontrolled

Controlled

Adaptive Sliding Phasor Averaged Control (ASPAC) able to prevent combustion instability



Controller off

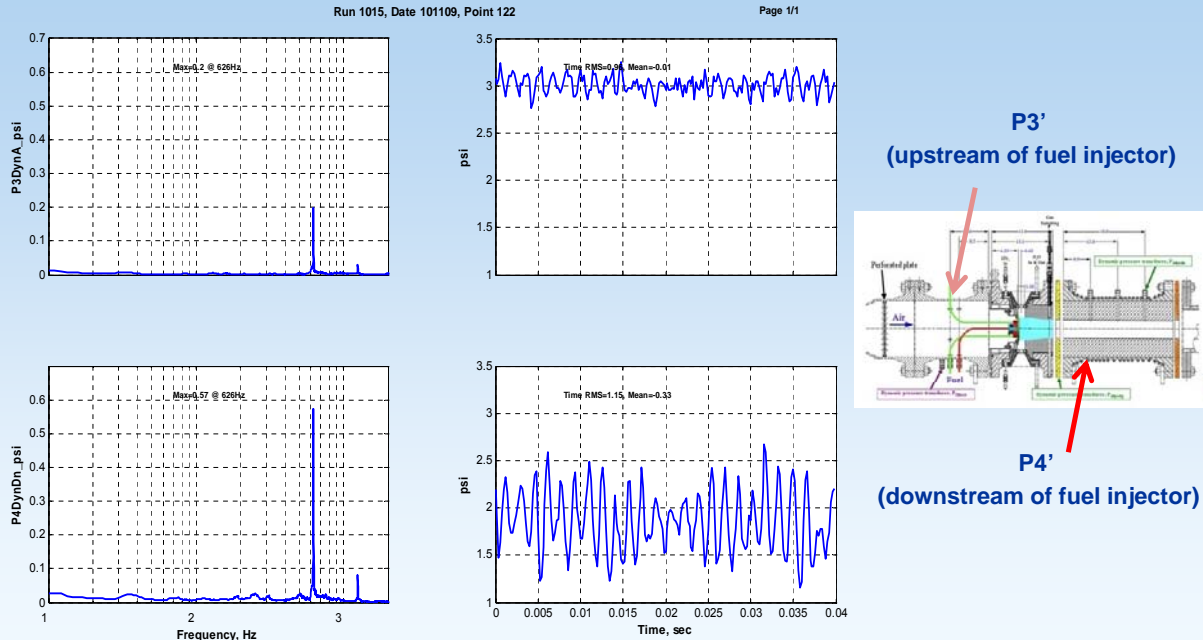
Controller on

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Use P3' (1000°F) rather than P4' (3000°F+) as feedback?



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Future Plans

Mature and demonstrate active combustion control technologies

- High temperature sensors, high-frequency fuel actuators and feed system models, combustion dynamics models, control methods
- Utilize Fundamentals rig in CE13C (5 atm) and medium/high pressure testing in CE5 (30 atm) and ASCR (60 atm)
- **Future platform(s) - LDI Multi-point injection and/or Industry advanced concepts**
 - Instability control demonstration(s) – 2012+
- **Other potential advanced technologies**
 - Control methods that exploit multipoint injection
 - Multidimensional models
 - Incorporate technologies from Fundamental Aeronautics NRA's
 - Harmonic, sub-harmonic models and control
 - Flame Transfer Function models
 - Dynamic stability margin management
 - Static instability (LBO) detection and control

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Long Term Goal for Active Combustion Control

- Improve fundamental understanding of the combustor processes

in order to...

- More effectively integrate multi-point combustor design, controls, sensor, and actuator technologies

to provide...

- An intelligent fuel/air management system with temporal and spatial fuel modulation for
 - Instability avoidance/suppression
 - Thermoacoustics, blowout
 - *Pattern factor control*
 - *Emissions minimization*



to enable...

- Combustors with extremely low emissions throughout the engine operating envelope

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References

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- Cohen, J.M. et al: "Experimental Replication of an Aeroengine Combustion Instability," International Gas Turbine & Aeroengine Congress & Exhibition, Munich, Germany, ASME Paper 2000-GT-0093, May 2000.
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- Cohen, J.M.; Proscia, W.; and DeLaat, J.C.: "Characterization and Control of Aeroengine Combustion Instability: Pratt & Whitney and NASA Experience." In "Combustion Instabilities in Gas Turbine Engines, Operational Experience, Fundamental Mechanisms, and Modeling", AIAA Progress in Astronautics and Aeronautics series, Tim Lieuwen, Vigor Yang editors, Chapter 6, p. 113-145, October 2005.
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- DeLaat, J.C.; Paxson, D.E.: "Characterization and Simulation of the Thermoacoustic Instability Behavior of an Advanced, Low Emissions Combustor Prototype." Presented at the 44th Joint Propulsion Conference and Exhibit cosponsored by the AIAA, ASME, SAE, and ASEE, Hartford, Connecticut, July 21-23, 2008. AIAA-2008-4878, NASA/TM-2008-215291.
- Saus, J.R.; Chang, C.T.; DeLaat, J.C.; Vrnak, D.R.: "Design and Implementation of a Characterization Test Rig for Evaluating High Bandwidth Liquid Fuel Flow Modulators. Presented at the 45th Joint Propulsion Conference and Exhibit cosponsored by the AIAA, ASME, SAE, and ASEE, Denver, Colorado, Aug. 2-5, 2009. AIAA-2009-4886.

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Questions?

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